Method to evaluate a heat and cold distribution in collective buildings with decentralised booster heat pumps

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Abstract

The development and use of more energy-efficient heating and cooling systems is required in order to secure a sustainable energy supply. In this respect, a myriad of concepts are being developed. The combined distribution circuit (CDC) of centralized heating at lower temperatures (ca. 20 to 30°C) or cooling and decentralized booster heat pumps (BHP) for the production of domestic hot water (DHW) is such a concept, notably one of a collective heating and cooling system for apartment buildings. Although certain studies have demonstrated that the use of BHP results in potential energy savings, no energetic evaluation of the BHP in a CDC is available.

In order to analyse all concept components a simulation environment in Matlab has been adapted. Therefore, new models are developed. This research compares the concept to a classic CDC with a supply temperature of at least 60°C heated by a central boiler. Moreover, the possible energy recuperations of this concept are quantified.

This research has shown that a CDC at lower distribution temperatures with BHP can achieve a total system efficiency of 334% on a yearly basis. Moreover, reducing the CO_2-emmisions with 55% is possible in comparison to a classic CDC. Thanks to the configuration of the heat interface unit (HIU), the BHP extracts between 10,2% to 31,5% of the total evaporator heat directly out of the apartment during summer. This study proofs that the concept of a CDC with BHP can contribute to decarbonizing the heat (and cooling) production in apartment buildings, while maintaining the desired comfort.

Keywords – Collective heating and cooling, booster heat pump, domestic hot water, energy system simulations

1. Introduction

Heat and cold production in apartment buildings

The heat demand in apartment buildings consists of two aspects, namely space heating (SH) and domestic hot water (DHW). In addition, the space cooling demand (SC) cannot be neglected anymore, as this energy demand is rising, because of higher insulation degrees, higher comfort demands, higher internal heat gains, etc. [1]. In Belgium, the implementation of central heating systems with collective heat production is increasing [2]. A centralised system facilitates the integration of sustainable installations, such as heat pumps (HP) or combined heat and power (CHP) [3]. Moreover, the installed power for DHW production can be reduced, by taking into account the simultaneity of the DHW demand in different apartments [4]. The implementation of a large central thermal energy storage (TES) will increase the thermal inertia and thus increasing the production efficiency [5]. Besides the energetic advantages, the benefits of economies of scale apply, making the initial investment per user cheaper than buying an individual renewable heat installation. Considering aforementioned energetic and financial advantages, a collective heating system is preferable [6], [7], [8]. The most important are the four-pipe system [9], which will not be considered in this research, and a two-pipe system in this paper introduced as a combined distribution circuit (CDC) (in Dutch called "combilus").

Combined distribution circuit

A CDC consists of two pipes, one supply and one return pipe connected to the central heat production to provide the technical hot water for SH or SC and DHW, and one (third) pipe supplying the domestic cold water (DCW) (see Fig. 1). Every apartment is connected to the CDC by a heat interface unit (HIU) to extract heat or cold from the CDC. The central production can also be a connection to a district heating network.
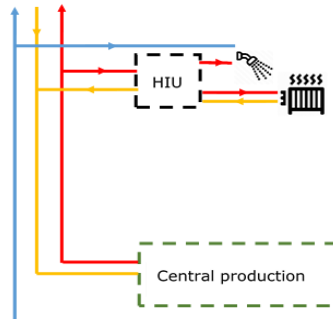

Fig. 1. main scheme of a CDC.

Lowering the distribution temperature in heating modus

The distribution losses in such systems are relatively increasing, due to the decreasing heat demand in the buildings, as the insulation degree in buildings is improving. Moreover, the relative demand for DHW and cooling is rising [1], [10].

By lowering the distribution temperature in heating modus, the distribution losses will lower. In this respect, the required temperatures for SH and DHW need to be taken into account. Underfloor heating, which is the main choice in ultralow-temperature networks, requires a range of supply water temperatures from 30°C to 45°C [11]. In order to consume DHW, a temperature of 40°C would be sufficient. However, avoiding the legionella bacteria growth requires 55°C or more [12]. On the other hand, in order to cool, a temperature of 22°C or lower is necessary [13].

Aforementioned contradictions can be reconciled by hybrid systems. This research proposes a method to supply the central heat at lower temperatures and to boost these temperatures on a local level (i.e. at every flat) in order to fulfil the needs of DHW. Such concepts have following advantages:

- The central geothermal heat pump (GHP) delivers heat at lower temperatures, which benefits the COP [14], [15]. This is interesting assuming the highest mass flow is heated by this GHP, and therefore the highest share of heat supply is generated at a higher COP.
- The distribution losses of the central pipes reduce.
- The higher temperatures occur only when and where necessary.

Obviously, the disadvantage of lower temperatures is the smaller design temperature difference (ΔT) between supply and return of central heat. As a result, the mass flow increases to deliver the same heating power and larger pipes are required. However, in this case (i.e. CDC in apartment buildings), the cost of the pipes is not as large as in district heating networks (DH).

A large amount of studies concerning low-temperature heating networks and BHPs has been performed. Østergaard and Andersen [16] have proven that an ultralow-temperature district heating network (ULTDH) with BHPs ("concept A") consume less energy than a LTDH, without BHPs ("concept B"). Moreover, the COP of the central HP is always higher in "concept A" than in "concept B". In latter study, a back-up boiler is used to cover the peak loads. Köfinger et al. [17] confirm that the BHPs are a valid solution for ULTDH and boost the temperature in an efficient way to store in a TES for apartment buildings or hotels. Kleefkens et al. [18] introduced an alternative configuration of the heat interface unit (HIU), where the BHP and floor heating tubes are connected via two valves. In this way, the heat

and cold recuperation during summer is possible. A study of Greenvis and EcoFys in the Netherlands [14] compared different LTDH options. They concluded that the BHPs are more efficient than air/water-HPs as a decentral DHW-producer. In addition, they confirmed that the BHP can use the internal excessive heat as a heat source during summer. The disadvantage of such systems is the place these TES take, especially for rather small apartments.

These studies have shown that the BHPs offer a potential to ULTDH and improve the performances. However, these studies are performed in large DH and do not take into account the hydronics of existing concepts due to the relative large time steps. When large time steps are used, the opening and closing of valves and the transient behaviour of installations is not taken into account. Moreover, the energy performances on building level have not been investigated, only on large scales (i.e. DH networks). For this reasons, it is required to perform studies to the energy performances of BHPs in smaller networks, such as an apartment building, with a small simulation time step. In this research, the BHPs implemented in a CDC at lower distribution temperatures is evaluated. A method to quantify the total system efficiency and the energy recuperations is developed, where the influence of various components can be examined. Furthermore, the comparison between the proposed concept and a classic CDC is made.

2. Methodology

A CDC with BHP could be analysed through in situ-measurements. However, the effect of the behaviour of inhabitants, such as the desired indoor temperature or the use of DHW, on the measurements is enormous. Furthermore, a realisation of the concept is required in order to measure.

By doing computer simulations, the characteristics of the installation (e.g. storage capacity, pipe lengths, temperature regimes) can vary to examine the influence of these changes, while the preconditions of user behaviour can be set. In this way, different energy-systems or variants of energy-systems can be compared in an objective way [4]. Finally, some points of attention can be discovered and taken into account before the realisation of the concept or installation [19].

Van Riet [20] has developed a simulation environment in Matlab, to study different hydronic circuits of hybrid heat and cold production. All the models have the same structure of flow rates and temperature inputs and outputs, which facilitates connecting the different models with each other. This simulation environment and some models are adapted to perform the presented concept study. Furthermore, a model of the BHP is developed.

Chapter 4 describes the studied concept in detail. However, a schematic overview of the energy flows is given in Fig. 2. The central production delivers heat or cold to the central distribution (CDC). The distributed temperature depends on the outdoor air temperature and is defined for the underfloor heating or cooling. This low temperature is heated up by the decentral BHPs to produce DHW, which is stored in the decentral domestic hot water storage TES.

The total system efficiency is the ratio of the total auxiliary energy (purple) to the total end user's energy (yellow). The auxiliary energy needed for the pumps in the systems are neglected, except when the central GHP is in cooling mode. The primary energy ratio (PER) is defined as the total system efficiency with the energy use converted to primary energy (for electricity, the used conversion factor is 2,5).
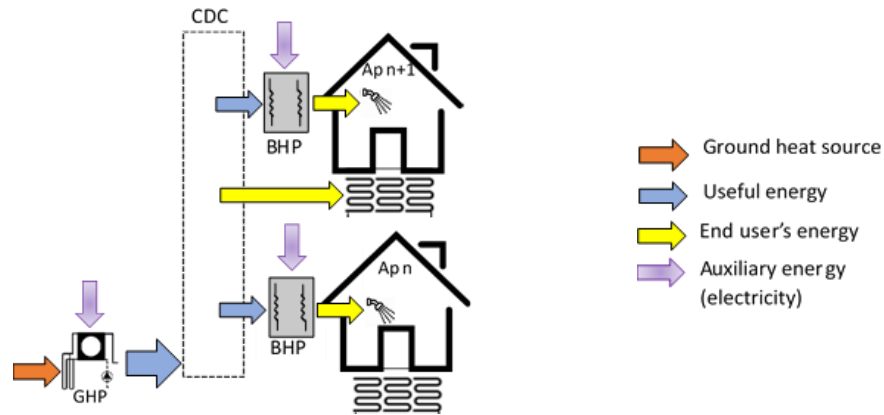
Fig. 2. schematic overview of energy flows in concept. In case of cooling, energy flow direction is inversed.

3. Models in simulations

In general, most models are discussed in [20]. However, this chapter gives an overview of the most important models used in the simulation environment and the new developed model of the BHP. It is important for this study that the models are an accurate reflection of reality, thus the interaction between different components and their transient behaviour is taken into account.

Demand profiles

A dynamic simulation consists, next to different models of components, of demand profiles. These demand profiles include the inhabitants' behaviour and weather profiles for Uccle (Belgium) [21]. A *profile generator* [22] of *Instal2020* [23] is used. The generated demand profiles are based on different family types, with each person characterized by its own weekly living pattern. The internal heat gains ($\dot{Q}_{met}$) consist of the number of "present persons" (i.e. 'awake' equals 120W and 'sleeping' equals 80W [24]) in the apartments and the heat losses of electrical appliances, which both daily varies.

The presence profile of inhabitants is directly linked to the DHW-demand in every dwelling, as only present inhabitants can consume hot water. In this respect, the configuration of the tapping points can be varied (i.e. number of taps, bath or no bath, one or two shower(s)).

Building

In the apartment building, 20 apartments are considered, with each the same lay-out (parameters) and model. A strong internal ventilation is supposed, hence every apartment is one thermic zone, without heat transfer to neighbouring apartments. A zone is described by the following 3R2C-model:
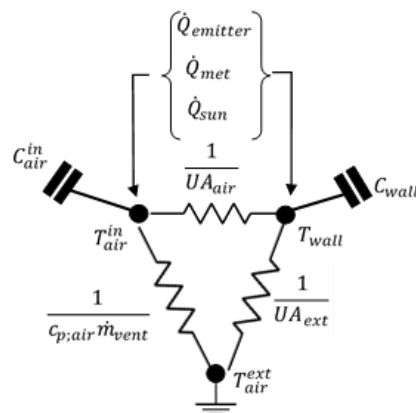

Fig. 3. 3R2C-model of zone (electrical analogy)

The heat flows $\dot{Q}_{emitter}$, $\dot{Q}_{met}$ and $\dot{Q}_{sun}$ are transferred to the air and the walls. In order to simulate the $\dot{Q}_{emitter}$, the floor heating is segmented in three equal parts with an uniform temperature, as done in other research [20]. The sum of emitted heat of every segment equals $\dot{Q}_{emitter}$ and is for 60% transferred to the air and 40% to the walls. However, in the case of cooling an apartment, the heat transfer of the emitter is negative and captures heat from the indoor air to heat up the emitter. The thermal capacity of the emitter (floor heating) is calculated as $C_{emitter} = 2240 \text{ kg/m}^3 \cdot 900 J/kgK \cdot 0,075m \cdot A_{floor}$ (with A_{floor} the floor area of the apartment [m²]).

$\dot{Q}_{met}$ is determined with the aforementioned *profile generator* and divided for 75% to the air and 25% to the walls. The solar radiation ($\dot{Q}_{sun}$) is equally (50%) divided over the air and wall heat capacity. Whereas the outdoor temperature (T_{air}^{ext}) and the solar radiation ($\dot{Q}_{sun}$) are values of a study, based on weather data from Uccle, Belgium [21].

The heat capacities C_{air}^{in} and C_{wall} [J/K] are resp. those of the air and the wall of a single apartment. C_{wall} equals 11,75 MJ/K, measured in the *Instal2020* project [23], while C_{air}^{in} is the product of the air volume (V_{air}) [m³], the specific heat capacity (c_p) [J/kgK] and mass density (ρ) [kg/m³] of air. In order to take into account the air temperature-gradient and heat storage in furniture a correction factor of five is applied (Jean Lebrun. Personal communication 21/05/2020).

The 3R-2C model consists of three temperature nodes, namely the outdoor temperature (T_{air}^{ext}), the indoor air temperature (T_{air}^{in}) and the temperature of the walls, floor and ceiling (T_{wall}). Between each node is an overall heat transfer coefficient (UA), in order to quantify the resistance of heat exchange. However, this resistance is different for ventilation losses. In this case, the heat losses depend on the mass flow through openings, such as crevices or windows (in summer), and is calculated as follows:

$$\dot{Q}_{vent} = c_{p;air} \dot{m}_{vent} \cdot \left(T_{air}^{in} - T_{air}^{ext} \right) \qquad (eq.1)$$

With $\dot{m}_{vent} = \frac{\rho_{air}}{3600} \cdot n_{venttot} \cdot V_{air}$ and $n_{venttot}$ is the ventilation rate per hour of the indoor air (hygienic minimums and blower-door test). In summer, when the indoor temperature is too high and the outdoor temperature is lower, an increased ventilation rate is considered to simulate the free cooling through windows during the night. The free cooling is taken into account, because, for this study, the cold demand is considered equally important as the heat demand.

The following two differential equations describe the behaviour of the indoor air temperature (T_{air}^{in}) and the walls temperature (T_{wall}). These equations are drawn from the 3R-2C model in Fig. 3.

$$C_{air}^{in} \frac{d\left(T_{air}^{in}\right)}{dt} = 0,6 \cdot \dot{Q}_{emitter} + 0,5 \cdot \dot{Q}_{sun} + 0,75 \cdot \dot{Q}_{met} - UA_{air} \cdot \left(T_{air}^{in} - T_{wall} \right)$$
$$- c_{p;air} \dot{m}_{vent} \cdot \left(T_{air}^{in} - T_{ext} \right) \qquad (eq.2)$$

$$C_{wall} \frac{d(T_{wall})}{dt} = 0,4 \cdot \dot{Q}_{emitter} + 0,5 \cdot \dot{Q}_{sun} + 0,25 \cdot \dot{Q}_{met} + UA_{air} \cdot \left(T_{air}^{in} - T_{wall} \right)$$
$$- UA_{ext} \cdot \left(T_{wall} - T_{ext} \right) \qquad (eq.3)$$

Model of central ground-source heat pump (GHP)

The central production unit is a ground-source heat pump. Its heating mode is modelled as in other research [20], [25]. The cooling mode is modelled as a counter-flow heat exchanger, according to the $\varepsilon - NTU$ method [26] in a static way. Furthermore, in the cooling mode, the auxiliary energy of the pumps is taken into account and calculated as follows:

$$P_{pumps}^{cool} = \dot{V}_{GHP} \rho g H / 3600 \qquad (eq.4)$$

With $\dot{V}_{EHP}$ the nominal mass flow of the central GHP $\left[5,7 \; ^{m^3}/_h\right]$, ρ the density of $\left[1000 \; ^{kg}/_{m^3}\right]$, g the gravitational acceleration $\left[9,81 \; ^m/_{s^2}\right]$ and H the head of the pump [m].

Model of the TES

The central TES is adapted from Van Riet [20] his storage vessel model. The mixing of a underlying warmer water layer in a TES is added to the model. This is necessary in the case when the central GHP is in cooling modus and stores it in the central TES from the upper inlet. The decentral TES for DHW have an internal spiral heat exchanger to separate the technical water from the DHW [20] and its storage volume is calculated by a so-called PV-curve [27], depending on the nominal heating power of the BHP.

Modelling of the CDC

The CDC and all other pipes in the concept are modelled by a plug-flow pipe model [28]. It is an efficient simulation method to take into account the transport delay in the pipes. The sum of the demanded mass flows for SH or SC and DHW of all apartments equals the total mass flow in this pipes. The hydraulic behaviour is not included in the model.

Model of booster heat pump

The model of the BHP is an adaptation of the model of a ground/water heat pump (GHP) [25]. The BHP-model is parametrized with the data of the *Alpha Innotec WWB21* from *Nathan Systems* [29], using a 'fit nonlinear regression model' from Matlab. As a result, the electrical power consumption and the heating power of the condenser can be determined, when the supply temperature of the evaporator (T_{in}^{src}) and the temperature of the condenser (T_{con}) are known.

$$\frac{\dot{Q}_{con}^{BWP}}{\dot{Q}_{th,nom}^{BWP}} = 2\,891,3 - 3\,268,7 \cdot T_{src} - 4\,201,9 \cdot T_{snk} + 4\,383,3 \cdot T_{src} \cdot T_{snk} + 539,5 \cdot T_{src}^2$$
$$+ 1\,500,4 \cdot T_{snk}^2 - 438,8 \cdot T_{snk} \cdot T_{src}^2 - 1\,398 \cdot T_{src} \cdot T_{snk}^2 \qquad (eq.\,5)$$

$$\frac{P_{elek}^{BWP}}{\dot{Q}_{th,nom}^{BWP}} = 593 - 556,7 \cdot T_{src} - 951,5 \cdot T_{snk} + 884,8 \cdot T_{src} \cdot T_{snk} + 10,8 \cdot T_{src}^2$$
$$+ 380 \cdot T_{snk}^2 - 10 \cdot T_{snk} \cdot T_{src}^2 - 348,6 \cdot T_{src} \cdot T_{snk}^2 \qquad (eq.\,6)$$

In equation 5 and 6, the temperatures are rescaled in order to offer the possibility to simulate with temperatures below 0°C and to have higher coefficients:

$$T_{src} = \frac{T_{in}^{src} + 273.15}{273.15} \quad and \quad T_{snk} = \frac{T_{con} + 273.15}{273.15} \qquad (eq.\,7\,\&\,eq.\,8, respectively)$$

With T_{in}^{src} en T_{con} in [°C].

The condenser and evaporator are considered as a lumped capacity, which means that $"T_{con} = T_{out}^{snk}"$, $"T_{eva} = T_{out}^{src}"$ and both sides store heat. Fig. 4 illustrates the mass and energy flows. This figure is used to derive the mass and energy balances of both the evaporator and condenser. The heat exchange between the capacity of the evaporator and the condenser is the energy flux $\dot{Q}_{eva}$.
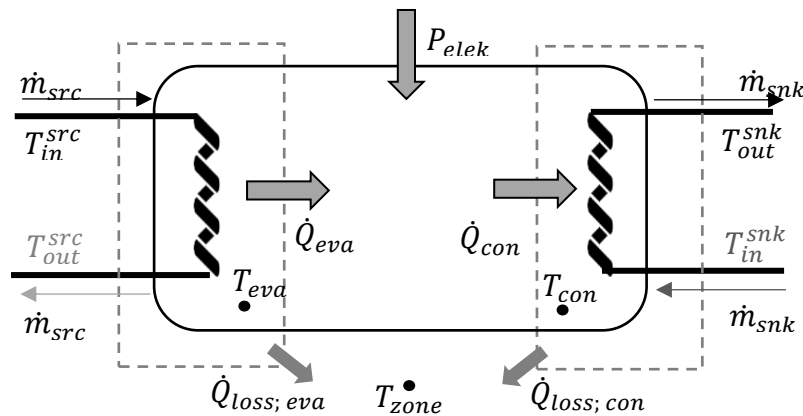

Fig. 4. The mass and energy balance of a booster heat pump

As showed in Fig. 4 the mass balance of both the evaporator and condenser consist of one mass flow per side. No mass storage is realized, thus the ingoing flow is equal to the outgoing flow.

The condenser delivers heat to produce DHW. The change of internal energy is:

$$C_{snk} \frac{dT_{out}^{snk}}{dt} = \dot{Q}_{con} - UA_{con} \cdot \left(T_{out}^{snk} - T_{zone} \right) + c_p \cdot \dot{m}_{snk} \cdot \left(T_{in}^{snk} - T_{out}^{snk} \right) \qquad (eq.\,9)$$

Where:

- C_{snk} [J/K] is the thermal capacity of the condenser.
- $\dot{Q}_{con}$ [W] from equation (eq. 5). The heating power of the condenser.
- UA_{con} [W/K] as in study [20] depending on the nominal heating power. In order to calculate the heat losses to the surroundings.
- $c_p \cdot \dot{m}_{snk} \cdot (T_{in}^{snk} - T_{out}^{snk})$ is the heat stored in the TES.

On the other hand, the evaporator extracts heat from the central CDC:

$$C_{src} \frac{dT_{out}^{src}}{dt} = -\dot{Q}_{eva} - UA_{eva} \cdot \left(T_{out}^{src} - T_{zone} \right) + c_p \cdot \dot{m}_{src} \cdot \left(T_{in}^{src} - T_{out}^{src} \right) \qquad (eq.\,10)$$

$\dot{Q}_{eva}$ is determined as follows:

$$\dot{Q}_{eva} = \dot{Q}_{con} - P_{elek} \qquad (eq.\,11)$$

With $\dot{Q}_{con}$ and P_{elek} resp. from (eq. 5) and (eq. 6). All other terms of (eq. 10) are similar to (eq. 9).

4. Case description and input parameters

In order to evaluate a concept, it is necessary to have a realistic energy demand. For this reason, a case study is used (see Fig. 5).

The case study includes heating as well as cooling and consists of three main parts, namely central heat production, heat (in winter) and cold (in summer) distribution via the CDC and 20 identical apartments with each a decentral production of DHW (BHP), a DHW thermal energy storage (DHW-TES) and underfloor heating, but a different heat demand profile. Because of the small apartment building (20
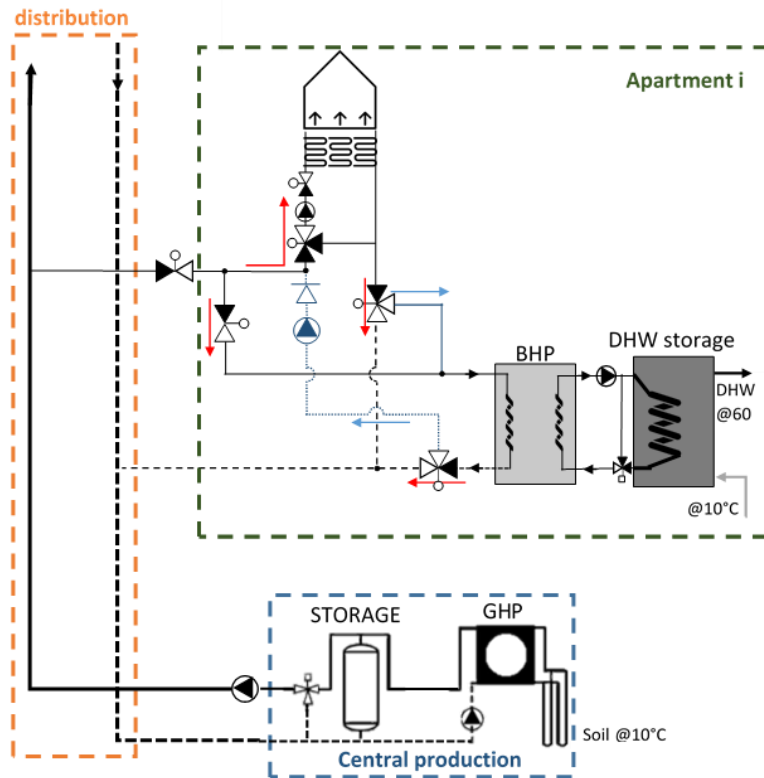

Fig. 5. installation scheme. In the winter, mass flow via red arrows and set-point of distribution is 25°C-35°C. In the summer, mass flow can follow blue arrows (if desired) and set-point of distribution is 18°C-20°C.

flats), no high pressures are assumed and a direct connection (no heat exchanger) between the distribution grid and the flats is used.

A central ground/water heat pump (GHP) and a TES form together the central heat and cold production. Furthermore, the GHP has, besides the heating function during winter, a cooling function in case the decentral BHPs do not provide sufficient cool load to the CDC. In other words, when the heat demand, needed to produce DHW, is not equal to the demand of cooling during summer days, central cooling is required in order to secure indoor air temperature comfort (i.e. not excessing the indoor air temperature set point). In contrast, when the BHPs produce DHW and no space cooling is needed, the BHPs could shut down as the central temperature becomes too low. Therefore, the GHP can also heat up the central water of the CDC during summer in described situation. The heating period (winter) starts September 15 and ends April 15, and the cooling period (summer) is from Mai 1 until August 30. During the other days, only heat in order to produce DHW is foreseen.

The control of the heat interface unit (HIU) differs from a conventional HIU, namely the interaction between space heating and DHW production is possible. A conventional HIU would separate the heat extraction as well as the return mass flows. In this way, no recuperation of the heat or cold would be possible. This innovative HIU-system is already described in the research of Kleefkens et al. [18]. During the space heating season, the central water flows along the red arrows in Fig. 5. The interaction is useful during summer, which is showed by the blue arrows in Fig. 5. On the one hand, the cold production of the BHP at the evaporator side (while it is producing DHW) can be consumed by the floor cooling, while a space cooling demand exists. On the other hand, the heated water after the space cooling (underfloor heating tubes) can be a heat source for the BHP in order to produce DHW. These two energy flows (Fig. 6. left-hand side) are the possible energy recuperations within the same apartment due to the configuration of the HIU.

Besides, an energy recuperation is also possible between different apartments, since the CDC distributes both the heat water for space heating/cooling and DHW. In this way, the cold produced by a BHP in apartment "n" can be useful for the space cooling in, for example, apartment "n+1" or any other apartment. Both the energy recuperation situation are shown in Fig 6. On the left hand side, the energy recuperation within one apartment is shown, while the scheme on the right hand side illustrates the energy recuperation between different apartments.
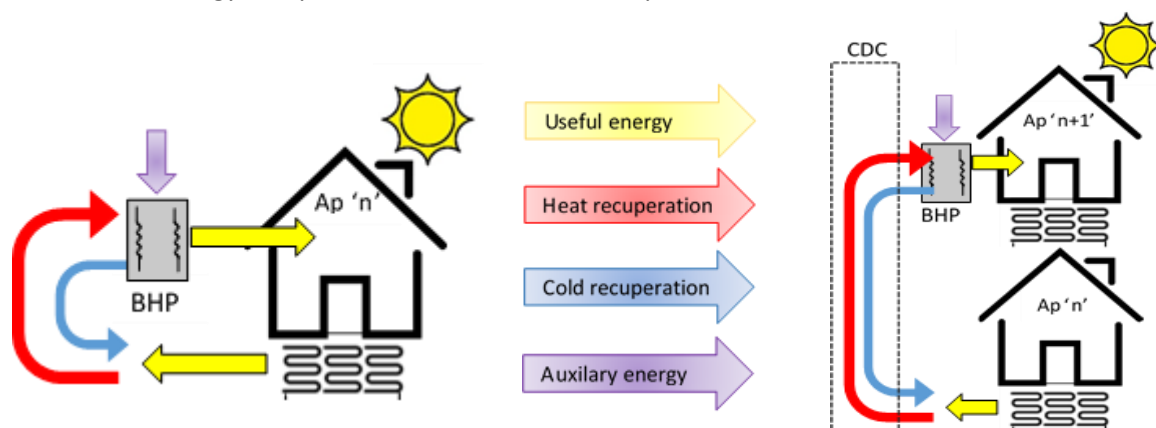

Fig. 6. heat recuperation in the same apartment (left hand side) or between different apartments, via the CDC (right hand side).

As mentioned before, the building consists of 20 identical apartments. The considered parameters to analyse the case study are listed:

- $\dot{Q}_{des}^{loss} = 0,7 \ ^W/_{m^2 K} \cdot 114 \ m^2 \cdot (21°C - (-8°C)) = 2320 \ W$; as the average UA-value is 80 W/K and the desired indoor temperature during winter is 21°C. In Belgium, the design outdoor temperature is -8°C.

- During the summer, the indoor temperature set point is 25°C.

- The floor area is 88 m², and a height of 3m, leads to a total air volume of 264 m³. As a result, the $C_{air}^{in} = \left(1.2 \ ^{kg}/_{m^3} \cdot 5\right) \cdot 1005 \ ^{J}/_{kgK} \cdot 264 \ m^3 = 1{,}6 \ ^{MJ}/_{K}$ and the heat capacity $C_{emitter} = 2240 \ ^{kg}/_{m^3} \cdot 900 \ ^{J}/_{kgK} \cdot 0.075m \cdot 88 \ m^2 = 13{,}3 \ ^{MJ}/_{K}$. The heat capacity of the walls is 11,75 MJ/K, as mentioned before.
- The ground source temperature is constantly 10°C through the year, no simulation of the soil is considered. The temperature of the domestic cold water also is constantly 10°C.
- The UA-values of the TES (central as well as decentral) is calculated according to the *eco-design guidelines* [30], with an energy class A.

Overall, the sum of heat and cold demands of the 20 apartments on a yearly basis is given in Table 1.

Table 1. yearly heat and cold demand of all 20 apartments.

SH demand	SC demand	DHW demand
23 MWh	11,97 MWh	42,98 MWh
29,5%	15,5%	55%

As can be seen in Table 1, the DHW demand is the largest part of the heat demand, as a result of the high insulation degree in the apartments, air tight building methods, higher internal gains, etc. In Belgium, a building is considered as new or as a nearly Zero Energy Building (nZEB), if the thermal energy demand is resp. 70 kWh/m²year or 15 kWh/m²year. In this case study, the average energy demand for space conditioning (SH and SC) is 20 kWh/m²year. This means that the apartment building is well insulated and is close to the requirements for a nZEB.

5. Results and discussion

The new simulation environment allows to investigate the energetical behaviour of the system. In this way, the energetical comparison with a classic CDC can be done. Furthermore, the possible energy recuperations are quantified.

Comparison to a classic CDC

A classic CDC is a collective heating network in an apartment building with a central boiler in order to produce the heat for SH and DHW. The design temperatures are high, usually 60°C/40°C and higher [31], and the cool load is not taken into account by the CDC. However, for this comparison, only characteristic efficiencies [16] are considered: a boiler efficiency of 95% and the cool demand is covered by decentral compression chiller, with an coefficient of performance (COP) of 4,5. This comparison is given in Table 2. The boiler efficiency is lowered to 90% in order to compensate the distribution losses in de CDC and central TES, because the distribution temperature is 60°C.

The total energy used by the CDC with BHPs is 23,35 MWh in order to fulfil the energy demands of the 20 apartments (listed in Table 1.). In this respect, the total system efficiency is 334% or, when converted to primary energy (58,375 MWh_PE), the PER is 133,5%. As a result, it can be stated that the CDC with BHP uses the energy sources in a sustainable way. In comparison (Table 2), the classic CDC has an energy consumption of 79,96 MWh_PE and the PER equals 97,5%. As a result, a primary energy saving of 27% is realised with the new concept.

Table 2. estimation of energy use of the classis CDC, with characteristic efficiencies. The classic CDC consist of a central boiler (SH + DHW) and decentral compression chillers (SC).

Classic CDC	Heat demand (SH + DHW)	Cold demand (SC)
system	Boiler	Compression chiller
efficiency	90%	COP = 4,5
Energy demand (Table 1)	65,98 MWh	11,97 MWh
Energy consumption	73,31 MWh	2,66 MWh
Conversion factor to PE	1	2,5
Total PE use :	79,96 MWh_{PE}	

Finally, a CO_2 analysis is shown in Table 3. For this analysis, the used conversion factor for electricity and natural gas are resp. 285 kg CO_2/MWh$_{el}$ and 202 kg CO_2/MWh. The concept with BHPs at lower distribution temperatures reduce the CO_2-emissions with 55% on a yearly basis. Furthermore, this concept does not emit any CO_2 on a local level, given that no fossil fuels are used locally.

Table 3. comparison of CO2-emissions of a classis CDC and the proposed concept.

Energy use	Classic	Concept
Natural gas	73,31 MWh	0 MWh
Electricity	2,66 MWh	23,35 MWh
CO2-equivalent	14,8 tons/year	6,65 tons/year

Energy recuperation

Finally, the possible energy recuperations thanks to the configuration of the HIU and CDC (i.e. the heat flows of SH and DHW are bundled and the possible interaction through the valves between the floor heating pipes and the BHPs) are simulated. This recuperations are only considered during the cooling season (i.e. the summer), as in this case, the excessive heat in the apartments can be used as a heat source for the BHPs. As a result energy recuperation in two ways is realized (i.e. cooling the apartments and provide a free heat source to the BHPs).

Table 4 shows the minimal, mean and maximal calculated energy recuperations of the apartments (via the HIU) for both the space cooling and DHW production. The minimal and maximal figures give an insight in the dependency of the family types in the apartments, as a two-person family uses less DHW than a four-persons family. The same assumption is made for the cooling demand. The total energy recuperation via the CDC is also given, including the energy recuperation in the same apartments and the energy recuperation between different apartments. The percentages are with respect to the cool demand or DHW demand during summer.

Table 4. realized energy recuperation and its share in the energy demands during summer.

Recuperation		In same apartment (blue arrows in Fig. 5.)			Via CDC	
Cooling	Min.	64,5 kWh	22,2%			
	Mean	163 kWh	27,2%	Tot : 3,26 MWh		
	Max.	236,8 kWh	28,2%			
					6,2 MWh	27,5%
BHP	Min.	44 kWh	10,4%			
	Mean	129 kWh	23,5%	Tot: 2,58 MWh		
	Max.	209,7 kWh	31,2%			

A considerably part is recuperated within the same apartment: from 22,2% to 28,2% of the cooling demand is directly generated by the BHP and used as a cool source. The family type has no large influence on this type of energy recuperation. It is supposed that the control strategy will have a larger influence, as the DHW production needs to be attuned to the cool demand.

On the other hand, a great variation is found in the range of heat recuperation to the BHP, namely 10,4% up to 31,2% of the BHP's heat source is derived from the indoor excessive heat. In this case, the family type has a great influence, as a two-person family generates more heat, thus more heat can be recovered by the BHP. In this respect, also the controlling will have an influence. However, when the cool load is larger, the chance that the DHW production is simultaneously with the cool demand is also increased.

Finally, the energy recuperation through different apartment is given. The 6,2 MWh includes the 3,26 MWh and 2,58 MWh of energy recuperation within the same apartments. In other words, only 0,36 MWh or 6% of the total energy recuperation is established in the CDC. An optimization of the control strategy is required in order to increase this percentage.

6. Conclusion

This research has investigated the energy performances of a ultralow temperature CDC with decentral BHPs. In this respect, the PE savings and CO_2-emissions are considered as important key factors. The case study consist of 20 identical apartments, with a different heat demand profile. The central production is a ground-coupled heat pump, without back-up fossil boilers. All apartments are equipped with a floor heating/cooling system and a BHP for DHW production with a storage tank.

In order to simulate the concept, an existing simulation environment of Van Riet [20] is adapted for a CDC with BHP. In this purpose, a BHP-model is developed and other models are adapted. The time step in the simulations is 10 seconds, in order to take into account the opening of valves and to obtain more detailed results.

The concept is compared to a classic CDC, namely a CDC at higher temperatures (60°C-75°C) with a central boiler. In this respect, characteristic efficiencies are used. The total system efficiency of the CDC with BHPs is 334% and its PER is 133,5%, while the PER of a classic CDC is 97,5%. Furthermore, a reduction of the CO_2-emission of 55% is possible with the proposed concept in this study. These energy savings are achieved by, on the one hand, the use of heat pumps, and on the other hand, the possible energy recuperations thanks to the configuration of the HIU.

All the results of this research show that the CDC at lower temperatures with decentralised BHP is a good, sustainable system to provide heating and cooling to apartment buildings.

Future work

The new developed simulation environment allows to investigate the impact of various design choices (e.g. the BHP's sizing or the central distribution temperature). In addition, the EPBD legislation has a major impact on system selection. However, its evaluation framework is not that detailed. In this respect, the developed simulation environment, needs to be compared to the EPBD standardization.

Furthermore, different configurations of this CDC with BHPs needs to be compared, in order to gain more insight in this type of heating and cooling network. This further research could lead to design rules to take into account by future realisations of the system.

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